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A novel design including cooling media for Lithium-ion batteries pack used in hybrid and electric vehicles

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HIGHLIGHTS

- The proposed battery pack has high thermal performance in comparison with others.
- Ultra uniform temperature and voltage distributions appear among the battery units.
- The maximum observed temperature and dispersion are less than those in other works.
- The increase in the battery pack volume is less than that in other works.
- Proposed battery pack has high thermal performance for ambient temperatures until 48 °C.

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ABSTRACT

In this paper, a novel design including cooling media for packing the rechargeable Lithium (Li)-ion batteries used in hybrid and electric vehicles is proposed. The proposed battery pack satisfies all thermal and physical issues relating to the battery packs used in vehicles such as operating temperature range and volume, and furthermore it increases the battery life cycle and charge and discharge performances. The temperature and voltage distributions of the proposed battery pack are calculated using the characteristics of a sample Li-ion battery and heat transfer principles. The proposed battery pack uses several distributed thin ducts for cooling which is based on distributed natural convection. Ultra uniform voltage and temperature distributions, minimum temperature dispersion in each battery unit, minimum increase in the battery pack volume, natural convection (no extra energy consumption for cooling), the maximum observed temperature less than that in other proposed battery packs and high thermal performance for different ambient temperatures until 48 °C are some advantages of the proposed Li-ion battery pack including proposed distributed cooling media. Simulation results and a comparison between the parameters of the proposed cooling media and other related work are presented to validate the theoretical results and to prove the superiority of the proposed battery pack design.

1. Introduction

Recently, the design of very advanced rechargeable batteries used in hybrid/electric vehicles has attracted many researches because using battery-powered hybrid/electric vehicles has many benefits especially regarding atmospheric air quality and energy consumption issues [1]. A Li-ion unit cell can provide a low voltage and power which is not suitable to apply in electric vehicles. So, to provide an appropriate rechargeable Li-ion battery pack for hybrid/electric vehicles, a numbers of unit cells have to be connected in series for increasing the battery voltage and also some parallel connections are necessary to raise the current capacity. The rechargeable Li-ion battery pack is recommended to use in hybrid/electric vehicles because of better life cycle, keeping charge in longer time, suitable generated power and reasonable cost in comparison with other kinds of the rechargeable batteries [2]. There is a similarity between the rechargeable Li-ion batteries and other kinds of the rechargeable batteries in generating heat during discharge cycle, so a high power discharge increases the generated heat and subsequently this raises rapidly the temperature of the unit cells in the Li-ion battery pack. The battery temperature which is higher than the recommended operating range causes serious problems for the battery such as damaging the unit cells and shortening the battery life. On the other hand, falling the temperature of a unit cell into below the desired temperature range causes a growing in the internal resistance and thus increasing in the voltage drop of the unit cell. It can be summarized that a

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Nomenclature

A	cross-sectional area [m^2]
E_{OC}	open-circuit voltage [V]
h	heat transfer coefficient [W m^{-2} °C^{-1}]
h_1	local heat transfer coefficient at $x = 0$ cm [W m^{-2} °C^{-1}]
h_2	local heat transfer coefficient at $x = 16$ cm [W m^{-2} °C^{-1}]
V_L	unit cell voltage [V]
Q	heat transfer/generation rate [W]
I	discharge current [A]
R_i	internal equivalent resistance of unit volume (Ω m^3)
S	entropy [J mol^{-1} K^{-1}]
ΔS	entropy change [J mol^{-1} K^{-1}]
ΔT_{Max}	maximum temperature dispersion [°C]
F	Faraday number (96485 [C mol^{-1}])
r	internal equivalent resistance [Ω]
q	heat transfer/generation rate [W]
$\dot{q}$	rate of internal heat generation per unit volume [W m^{-3}]
i	discharge current of a Li-ion unit cell per unit volume [A m^{-3}]
SOC	state of charge
α	thermal diffusivity [m^2 s^{-1}]
k	thermal conductivity [W m^{-1} °C^{-1}]
C_0	electric capacity of battery [Ah]
T_i	ambient temperature [°C]
$T_{L \cdot Wall}$	temperature of the left battery unit [°C]
$T_{R \cdot Wall}$	temperature of the right battery unit [°C]
ΔV	volume of the air flowing through the duct [m^3]
W	depth of the cooling ducts [m]
T_{air}	temperature of the air flowing through the cooling duct [°C]
$T_{air-input}$	air temperature in the entrance of the cooling duct [°C]
V_{Air}	velocity of the air flowing through the cooling duct [m s^{-1}]

rechargeable Li-ion battery pack used in hybrid/electric vehicles represents the best performance when it operates in the desired temperature range and furthermore, the temperature distribution along the unit cells of the battery pack is as uniform as possible. To guarantee the operation of the battery pack in the desired temperature range, an appropriate battery pack design is necessary. To design an appropriate battery pack, temperature-dependent battery performance characteristics and also related models must be evaluated. For this purpose, the temperature distribution within the battery pack is the most important characteristic which have to be evaluated. A model of cooling process in Li-polymer electrolyte batteries was presented in Ref. [3]. The proposed model provided a temperature distribution and it was shown that the obtained temperature distribution can be improved using cooling system and also applying better insulation materials. Thermal properties of cylindrical and prismatic Li-ion unit cells including heat generation during the discharge process and vice versa, heat consumption during the charge process under various state of charge (SOC) were measured in Ref. [4]. For first time, a natural (passive) cooling system using phase change material (PCM) was designed for a Li-ion battery in Ref. [5]. The results of a comparison between passive cooling using PCMs and forced air cooling verified that at high ambient temperatures or high discharge rates, natural air cooling is not a suitable cooling system to guarantee that the battery operates in the desired temperature range, so forced air cooling using fan power is necessary [6,7]. The transient response and numerical results of the temperature distribution in the cylindrical and prismatic Li-ion battery during a discharge cycle were presented in Ref. [8]. The results showed that the temperature of the battery with the laminated cross section is less than that in the battery with square cross section during a discharge cycle. A new model of Li-ion cell based on an electrochemical–thermal-coupled and a comparison between the two mechanisms consisting of the individual electrode and three-electrode cell were presented in Ref. [9]. As another research work, thermal management of battery modules using PCMs under different battery discharge conditions and variable ambient temperatures was studied in Ref. [10]. A thermal model of a cylindrical $LiFePO_4$/graphite Li-ion battery was presented in Ref. [11]. Based on the proposed model, heat transfer coefficients, heat capacity and steady-state temperature were experimentally measured and consequently, the battery thermal resistance was calculated. A coupled electrical–thermal model of a Li-ion cell including equivalent electrical and thermal circuits was presented in Ref. [12]. This model represents the electrical–thermal behavior of the Li-ion cell and it can be used to predict the thermal and electrical responses of the Li-ion cell. As a latest and related work, a comparison between forced cooling and natural cooling of a Li-ion battery pack was reported in Ref. [13].

Thermal management of a Li-ion battery pack means that all Li-ion unit cells and battery units of the battery pack operate at a desirable average temperature with as small as possible voltage and temperature variations as recommended by the battery manufacturer. It is clear that the cooling media of a battery pack plays an essential role in thermal management of the battery pack.

This paper presents a novel design including proposed cooling media for a Li-ion battery pack which is used in hybrid and electric vehicles. Heat generation concepts for a thin-film flat Li-ion cell are presented in Section 2. Thermal analysis of the proposed battery pack is done using the partial equations, which describe the temperature distribution in the battery pack, and related boundary conditions. In Section 3, the temperature distribution in the proposed battery pack is calculated using the numerical solution of the mentioned equations. Simulation and numerical results for the proposed battery pack including cooling media are presented in Section 4. The internal resistances of each battery unit and as a result, the voltage distribution among the battery units are calculated. Performance curves including temperature and voltage distributions are plotted. Ultra uniform temperature and voltage distributions, minimum temperature dispersion in each battery unit, minimum increase in the battery pack volume, natural convection (no extra energy consumption for cooling), and the maximum observed temperature less than that in other battery pack designs are some advantages of the proposed Li-ion battery pack. As will be shown the proposed Li-ion battery pack design has high thermal performance for different ambient temperatures until 48 °C, so it can be used in most points of the world.

2. Heat generation in a Li-ion unit cell

Thin-film flat Li-ion unit cell is generally used to construct a battery pack for electric vehicles because of its appropriate size and shape. A thin-film flat Li-ion unit cell consists of a positive electrode composed of a thin layer of powdered metal oxide such as $LiCoO_2$ mounted on aluminum foil and a negative electrode constructed from a thin layer of powdered graphite, or other certain carbons, mounted on a thin copper foil. The two electrodes are separated by a porous plastic film soaked typically in $LiPF_6$ dissolved in a mixture of organic solvents such as ethylene carbonate, ethyl methyl

carbonate, or diethyl carbonate [14]. Several Li-ion unit cells are used to perform a battery unit. Chemical processes in the Li-ion unit cell during the charge and discharge cycles can be summarized as

$$LiCoO_2 + C_6 \rightleftarrows CoO_2 + LiC_6 \tag{1}$$

where the above chemical reaction proceeds from left to right side during the charge cycle and it proceeds in opposite direction (right to left side) during the discharge cycle.

The heat generation rate in a Li-ion unit cell can be found as [3]:

$$q = I\cdot(E_{OC} - V_L) - I\cdot T\frac{dE_{OC}}{dT} \tag{2}$$

where q is the heat generation rate, I is the current passing through the unit cell so that $I > 0$ during the discharge cycle and $I < 0$ during the charge cycle, E_{OC} is the open-circuit voltage of the unit cell, V_L is the cell voltage, T is the cell temperature and dE_{OC}/dT is the temperature coefficient. The first term, $I\cdot(E_{OC} - V_L)$, is heat generation caused by current transfer across the internal resistances available in the cell and the second term, $-I\cdot TdE_{OC}/dT$ is the heat generated or consumed during the discharge or charge cycle, respectively. This term is produced by the reversible entropy change resulting from the cell electrochemical reactions [3,13]. It is clear that different kinds of Li-ion cells have different values of the internal resistances and entropy changes. The internal equivalent resistance of a unit cell depends on both the temperature and SOC of the battery, so it is measured under various battery temperatures and SOC [8]. The internal equivalent resistance for the commercial small size Li-ion battery (SONY-US18650) was measured as a function of SOC and temperature in Ref. [8]. Using these experimental data, the internal equivalent resistance of unit volume can be expressed as

$$R_i = \begin{cases} 2.258\times10^{-6}SOC^{-0.3952}; & T = 20^\circ C \\ 1.857\times10^{-6}SOC^{-0.2787}; & T = 30^\circ C \\ 1.659\times10^{-6}SOC^{-0.1692}; & T = 40^\circ C \end{cases} \tag{3}$$

where R_i is the internal equivalent resistance of unit volume (Ω m^3) of the Li-ion battery. The parameters of this type of the Li-ion batteries are same as the thin-film flat type because of their similar structures. In this paper, these experimental data are used to design an optimal rechargeable Li-ion battery pack consisting of thin-film flat Li-ion unit cells. The entropy change (ΔS) is defined as

$$\Delta S = F\frac{dE_{OC}}{dT} \tag{4}$$

where F is Faraday number (96485 [C mol^{-1}]). By substituting dE_{OC}/dT from Eq. (4) into Eq. (2), it can be derived that

$$q = I^2\cdot\frac{(E_{OC} - V_L)}{I} - I\cdot T\frac{\Delta S}{F} \tag{5}$$

or

$$q = I^2\cdot r - I\cdot T\frac{\Delta S}{F} \tag{6}$$

where r is the internal equivalent resistance of the unit cell. By dividing right and left sides of Eq. (6) to the volume of the unit cell (V), Eq. (6) can be rewritten as

$$\dot{q} = \frac{q}{V} = \frac{I^2}{V^2}\cdot(r\cdot V) - \frac{I}{V}\cdot T\frac{\Delta S}{F} \tag{7}$$

or

$$\dot{q} = R_i\cdot i^2 - i\cdot T\frac{\Delta S}{F} \tag{8}$$

where $\dot{q}$ is the rate of internal heat generation per unit volume and i is the discharge current of a Li-ion unit cell per unit volume. It is reminded that the second term of the Eq. (8) is positive during the discharge cycle ($\Delta S < 0$) and it is negative during the charge cycle ($\Delta S > 0$). The experimental results show that during the discharge cycle, ΔS over a range of temperature between about 18 °C and 42 °C is almost independent of the temperature [8]. In this range of the temperature ΔS is only a function of SOC which can approximately be expressed as

$$\Delta S \approx \begin{cases} 99.88\,SOC - 76.67; & 0 \le SOC \le 0.77 \\ -30; & 0.77 < SOC \le 0.87 \\ -20; & 0.87 < SOC \le 1 \end{cases} \tag{9}$$

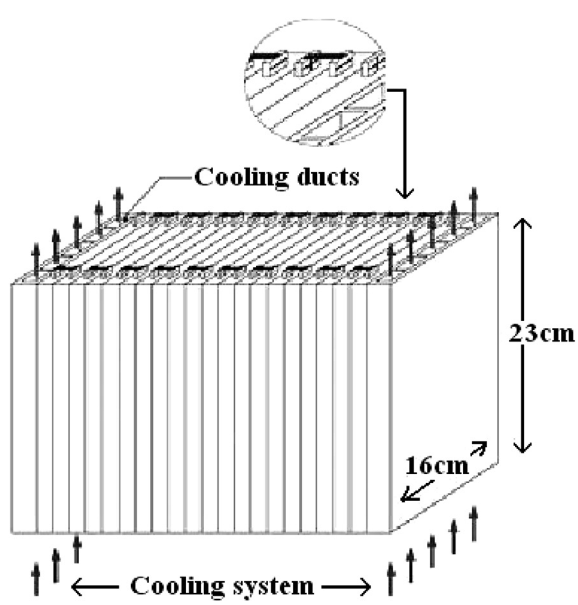

Fig. 1. Schematic of the battery pack with 20 battery units and two surrounding cooling ducts.

3. Temperature distribution in a Li-ion unit cell

The schematic of a typical and commercial Li-ion battery pack used in electric vehicles is shown in Fig. 1. The cooling of the battery is provided by two cooling ducts mounted at both ends of the battery pack [13,15]. This battery pack consists of 20 battery units connected in series. Each battery unit itself consists of 10 thin-flat Li-ion unit cells connected in parallel. One thin-flat Li-ion unit cell consists of seven layers including Graphite, Cu, Graphite, electrolyte, $LiCoO_2$, Al, $LiCoO_2$ and also separator [15]. The total thickness of one thin-flat Li-ion unit cell is 730 μm and its dimensions are 730 μm (thickness) × 16 cm (wide) × 23 cm (tall). So, considering the total thickness of the cover of a battery unit about 0.7 mm results that the dimensions of a battery unit are 8 mm (thickness) × 16 cm (wide) × 23 cm (tall). The open circuit voltage and electric capacity of each Li-ion unit cell are 3.6 V and 2 Ah, respectively, so the open circuit voltage and electric capacity of each battery unit are 3.6 V and 20 Ah and consequently these parameters for the Li-ion battery pack are 72 V and 20 Ah, respectively. All data including the battery pack configuration and the

Table 1
Configuration of the commercial Li-ion battery pack used in electric vehicle.

Battery	
Number of unit cells per battery unit	10
Number of battery units in the pack	20
Cell surface area [cm^2]	368
Electric capacity of each unit cell [Ah]	2
Electric capacity of each battery unit [Ah]	20
Open-circuit voltage of each unit cell [V]	3.6
Cut-off state of charge [%]	20

thickness of a Li-ion unit cell layers are summarized in Table 1 and Table 2.

As mentioned above, one thin-flat Li-ion unit cell consists of seven layers including Graphite, Cu, Graphite, electrolyte, $LiCoO_2$, Al, $LiCoO_2$ and also separator [15]. The temperature distribution in each layer of the thin-flat Li-ion unit cell can be calculated using the following partial equation [8,13,15]:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\dot{q}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{10}$$

where x and y are the spatial directions on x and y coordinate axes, respectively, α is the thermal diffusivity and k is the thermal conductivity. By replacing $\dot{q}$ from Eq. (8) in Eq. (10), it can be derived that

$$\nabla^2 T = \frac{1}{\alpha}\frac{\partial T}{\partial t}+\frac{\Delta S\cdot i}{k\cdot F}T-\frac{R_i\cdot i^2}{k} \tag{11}$$

The SOC is defined as

$$\mathrm{SOC} = 1-\frac{I\cdot t}{C_0} \tag{12}$$

where I is the discharge current ([A]), C_0 is the electric capacity of the proposed battery ($C_0 = 20$ [Ah]) and t is the discharge duration ([h]). Replacing $t = 0$ in Eq. (12) results that SOC is one (SOC = 1), this means that the battery has full charge when simulation starts. Now, the entropy change can be found by substituting SOC = 1 in Eq. (9), so $\Delta S = -20$ [$\mathrm{J\,mol^{-1}\,K^{-1}}$] and replacing this value and $F = 96485$ [$\mathrm{C\,mol^{-1}}$] in Eq. (11) results that

$$\nabla^2 T = \frac{1}{\alpha}\frac{\partial T}{\partial t}-\frac{20\cdot i}{96485\cdot k}T-\frac{R_i\cdot i^2}{k} \tag{13}$$

or

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t}-\frac{20\cdot i}{96485\cdot k}T-\frac{R_i\cdot i^2}{k} \tag{14}$$

Thermal conductivity (k) and other thermal–physical properties for the different layers of the Li-ion unit cell are presented in

Table 2
Thickness of a Li-ion unit cell layers extracted from US18650 Lithium-Ion Battery Manual, Sony Co. [15].

Thickness of cell layers [μm]	
Graphite	120
Cu	20
Graphite	120
Electrolyte	40
$LiCoO_2$	180
Al	20
$LiCoO_2$	180
Separator	50
Total thickness of a unit cell [μm]	730

Table 3
Thermal–physical properties for the different layers of the Li-ion unit cell [15].

Property	Cu	Graphite	Electrolyte	$LiCoO_2$	Al	Separator
k [$\mathrm{W\,m^{-1}\,{}^\circ C^{-1}}$]	398	1.04	0.59	4	237	0.35
ρ [$\mathrm{kg\ m^{-3}}$]	8930	1347	1223	2700	2710	1400
c [$\mathrm{J\ kg^{-1}\,{}^\circ C^{-1}}$]	386	1437	1375	715	902	1551

Table 3. As mentioned before, i is the discharge current of a Li-ion unit cell per unit volume and a decline in i appears during the battery discharge. This parameter has been measured in Ref. [8]. The temperature distribution in each layer of the thin-flat Li-ion unit cell can be calculated form Eq. (14). The partial Eq. (14) needs the initial and boundary conditions in order to be solved. Since all Li-ion unit cells of the proposed Li-ion battery pack are at an initial temperature which is ambient temperature (T_i), so initial condition can be expressed as

$$\forall x, \forall y;\ T(x,y,0) = T_i = 20^\circ C \tag{15}$$

The boundary conditions can be determined by considering the effects of the proposed cooling media due to the exposure of the unit cells and battery pack to the ambient via the proposed cooling system and battery pack container. The top view of the proposed distributed cooling media is shown in Fig. 2. Cooling is done by flowing air through the proposed ducts. As mentioned before, the surface of each thin-flat Li-ion unit cell has the dimensions of 16 cm wide and 23 cm tall, thus each battery unit consisting of 10 thin-flat Li-ion unit cells connected in parallel has the same wide and tall, in other words, $0 \le x \le 16$ cm and $0 \le y \le 23$ cm. The battery pack design including the proposed cooling media, which has been detailed respecting to the x and y coordinate axes, is shown in Fig. 3. This figure shows that each duct located between two battery units itself consists of 8 small mini ducts with the dimensions of 2 cm × 1.5 mm. The temperature variation of the air flowing through the each duct of the proposed cooling system can be expressed by following discrete equation:

$$\rho\cdot\Delta V\cdot c\frac{\Delta T_{air}}{\Delta t}+\dot{m}c\Delta T_{air}-h\cdot\Delta S\cdot(T_{L\cdot Wall}+T_{R\cdot Wall}-2T_{air}) = 0 \tag{16}$$

where $T_{L\cdot Wall}$ and $T_{R\cdot Wall}$ are the temperatures of the left and right battery units, respectively (for example battery unit#2 and #1, respectively), ΔV volume of the air flowing through the duct during the Δt and ΔS is the surface of the duct wall (right or left wall)

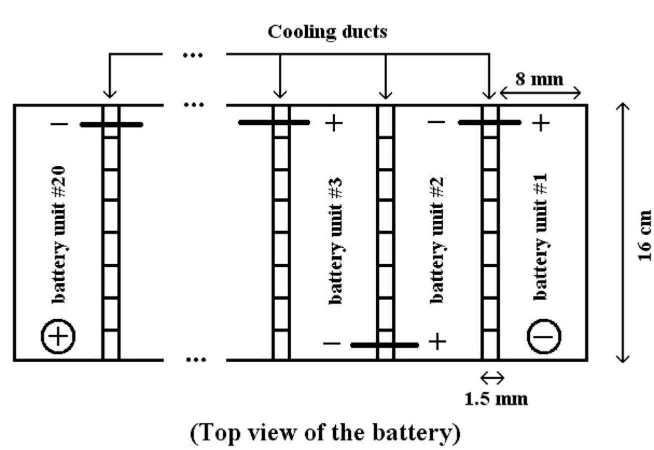

Fig. 2. Top view of the proposed distributed cooling media.

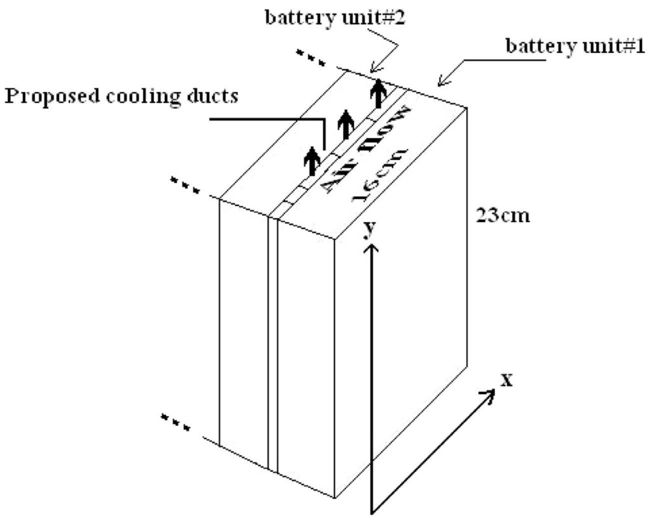

Fig. 3. Battery pack design including the proposed cooling media.

passed by air flow during the Δt. By replacing $\Delta V = A\Delta y$ and $\Delta S = W\Delta y$, Eq. (16) can be rewritten as

$$\rho \cdot A \cdot \Delta y \cdot c \frac{\Delta T_{\text{air}}}{\Delta t} + \dot{m}c\Delta T_{\text{air}} - h \cdot W \cdot \Delta y \cdot (T_{\text{L·Wall}} + T_{\text{R·Wall}} - 2T_{\text{air}}) = 0 \tag{17}$$

where W is the duct depth of the proposed ducts ($W = 16$ cm) and A is the cross-sectional area of each duct ($A = 16$ cm $\times$ 1.5 mm $= 240$ mm^2). After passing enough time, the steady state appears in the duct, the steady state response is independent of time, so the first term of the discrete Eq. (17) can be ignored. This simplifies Eq. (17) as following

$$\Delta T_{\text{air}} = \frac{hW}{\dot{m}c}(T_{\text{L·Wall}} + T_{\text{R·Wall}} - 2T_{\text{air}})\Delta y \tag{18}$$

Eq. (18) can easily be solved numerically using the following boundary condition:

$$T_{\text{air}}(y)|_{y=0} = T_{\text{air-input}} = T_{\text{i}} = 20^\circ\text{C} \tag{19}$$

where $T_{\text{air-input}}$ is the air temperature in the entrance of the duct ($y = 0$). After finding $T_{\text{air}}(y)$as a numerical solution of Eq. (17), the boundary conditions for the partial Eq. (14) can be found as

$$\left.\frac{\partial T(x,y,t)}{\partial x}\right|_{x=0\ \text{cm}} = \frac{h_1}{k}|T(0,y,t) - T_{\text{air}}(y)| \tag{20}$$

and

$$\left.\frac{\partial T(x,y,t)}{\partial x}\right|_{x=16\ \text{cm}} = \frac{h_2}{k}|T(16,y,t) - T_{\text{air}}(y)| \tag{21}$$

where h_1 and h_2 are the local heat transfer coefficients at $x = 0$ cm and $x = 16$ cm, respectively. Now, the temperature distribution in each layer of the thin-flat Li-ion unit cell can be calculated using the numerical solution of Eq. (14) along with the initial condition expressed by Eq. (15) and boundary conditions expressed by Eqs. (20) and (21).

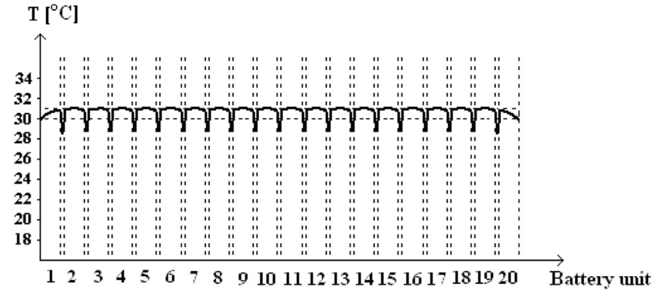

Fig. 4. Temperature distribution at the midplane of the proposed battery pack, discharging rate of 2 C from SOC = 1 to SOC = 0.2, (cooling media: air, natural convection, the cross-sectional area of each duct 16 cm $\times$ 1.5 mm, $V_{\text{Air}} = 0.01$ [m s^{-1}], $h = 37.5$ [W m^{-2} °C^{-1}]).

4. Calculation and simulation results

As mentioned before, the discharge process starts from SOC = 1 and ends to SOC = 0.2 with the discharge rate of 2 C. It means that the battery will be fully discharged after half an hour. The proposed cooling media consists of: air as fluid, natural convection, air velocity $V_{\text{Air}} = 0.01$ m s^{-1}, heat transfer coefficient $h = 37.5$ W m^{-2} °C^{-1} and ambient temperature ($T_{\text{i}} = 20$ °C). Fig. 4 shows the temperature distribution at the midplane ($y = 11.5$ cm) of the battery pack after 24 min when the battery SOC reaches 20% (SOC = 0.2). This figure clearly shows that the temperature distribution in the each individual battery units (excluding the two battery units mounted at both ends of the battery pack) is ultra uniform with a maximum temperature dispersion less that 0.05 °C ($\Delta T_{\text{Max}} \leq 0.05$ °C), and the maximum observed temperature is $T_{\text{Max}} = 31$ °C. For the two battery units located at both ends of the battery pack, the maximum observed temperature is $T_{\text{Max}} = 30.8$ °C with a maximum temperature dispersion less than0.8 °C. The intermediate plunges in the temperature distribution represent the local air temperature in the cooling ducts. The voltage of each battery unit at the end of the discharge process (after 24 min) is shown in Fig. 5. It can clearly be seen that the voltage distribution is very uniform. The percent of the voltage regulation is defined as

$$\Delta V\% = 100\frac{V_{\text{Max}} - V_{\text{Min}}}{V_{\text{ave}}} \tag{22}$$

where V_{ave}, V_{Max} and V_{Min} are the average, maximum and minimum voltage observed between all battery units of the proposed battery pack, respectively. For the proposed cooling media and battery pack, the minimum voltage (3.48 [V]) is observed in two battery units located at both ends of the battery pack and the maximum voltage is observed in middle battery units, so the percent of the voltage regulation is about 1.98%. The extra proposed cooling ducts increase the volume of the battery pack. The percent of the increase in the volume can be calculated as

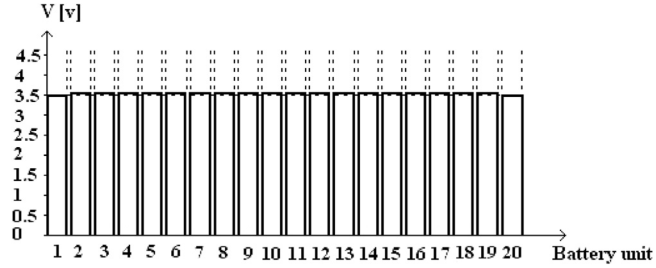

Fig. 5. Voltage of each battery unit at the end of the discharge process.

Table 4
Comparison between the parameters of the proposed cooling media in this work and the latest related work [13].

Parameter	This work	[13]
Maximum observed temperature in middle battery units (T_{Max}) [°C]	31	36
Maximum temperature dispersion in middle battery units (ΔT_{Max}) [°C]	0.05	0.2
Maximum observed temperature in battery units located at both ends of the battery pack (T_{Max}) [°C]	30.8	35
Maximum temperature dispersion in battery units located at both ends of the battery pack (ΔT_{Max}) [°C]	0.8	1
The percent of the voltage regulation ($\Delta V\%$)	1.98	>2[a]
The percent of the increase in the volume of the battery pack (ΔVol.%)	17.81	22.5[b]

[a] It is derived from Fig. 13 of [13].
[b] $\Delta\text{Vol.\%} = 100((9 \times 16\text{ cm} \times 23\text{ cm} \times 4\text{ mm})/(20 \times 16\text{ cm} \times 23\text{ cm} \times 8\text{ mm})) = 22.5\%$.

$$\Delta\text{Vol.\%} = 100\frac{\Delta\text{Vol.}}{\text{Vol.}} = 100\frac{19 \times 16\text{ cm} \times 23\text{ cm} \times 1.5\text{ mm}}{20 \times 16\text{ cm} \times 23\text{ cm} \times 8\text{ mm}} = 17.81\% \tag{23}$$

where ΔVol. is the increase in the volume of the battery pack after adding the proposed distributed ducts and Vol. is the volume of the battery pack without any ducts.

The above numerical solutions and simulations were carried out at ambient temperature of 20 °C but increasing in ambient temperature until 48 °C can not cause to operate the proposed battery pack out of the appropriate/recommended temperature range (below60 °C). Even for ambient temperature higher than 48 °C until 55 °C a forced convection ($V_{Air} = 1\text{ m s}^{-1}$) using a suitable fan located above the proposed battery pack causes to operate the battery in the appropriate/recommended temperature range.

For providing a comprehensive comparison and evaluation, a comparison between the parameters of the proposed cooling media in this work and the latest related work [13] is presented in Table 4. The comparison explicitly shows the superiority of the proposed cooling media to other work although this work uses natural convection and the other work uses forced convection. By considering Figs. 4 and 5 and Table 4, some advantages of the proposed cooling media for the Li-ion battery pack can be summarized as:

- Ultra uniform temperature and voltage distributions appear among the battery units.
- The maximum observed temperature is less than that in other works.
- The maximum temperature dispersion is less than that in other works.
- The increase in the battery pack volume because of adding the proposed cooling ducts is less than that in other works.
- The proposed cooling media is based on natural convection, so there is not any extra energy consumption/loss for cooling purpose. Consequently, extra devices such as electrical motors (fans) are not necessary.
- The proposed design of Li-ion battery pack has high thermal performance for different ambient temperatures until 48 °C, so it can effectively be used in most points of the world.

5. Conclusion

This paper presented a novel design including proposed cooling media for a Li-ion battery pack which is used in hybrid/electric vehicle. Thermal analysis of the proposed battery pack was done using the partial equations which describe temperature distribution in the battery pack together with the related boundary conditions. The temperature distribution in the proposed battery pack was calculated using numerical solution of the mentioned equations. The internal resistance of each battery unit and consequently the voltage distribution among the battery units was calculated. Performance curves including temperature and voltage distributions were plotted. Ultra uniform temperature and voltage distributions, minimum temperature dispersion in each battery unit, minimum increase in the battery pack volume, natural convection (no extra energy consumption for cooling) and the maximum observed temperature less than that in other proposed battery pack are some advantages of the proposed Li-ion battery pack including distributed cooling media. The numerical solutions and simulations were carried out at ambient temperature of 20 °C but it was shown that increasing in ambient temperature until 48 °C can not cause to operate the proposed battery pack out of the appropriate/recommended temperature range (below60 °C). Even for ambient temperature higher than 48 °C until 55 °C a forced convection using a suitable fan located above the proposed battery pack causes to operate the battery in the appropriate/recommended temperature range. So the proposed battery pack has optimal thermal performance when it is used in most points of the world with different ambient temperatures. A comparison between the parameters of the proposed cooling media and the latest related work explicitly showed the superiority of the proposed cooling media to other related work.

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